

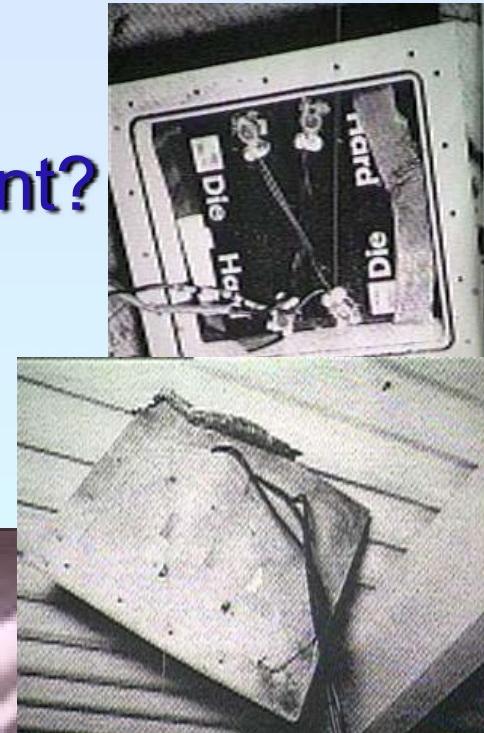
Hydrogen Hazards Assessment

Hydrogen Hazards Assessment Protocol (HHAP)

Approach and Methodology

Overview

- Why perform hazards assessment?
- Types of hazard assessment
- Analyzing hydrogen hazards
- Introduce the HHAP
- Methodology
- Summary



Why Perform Hazards Assessment?

Hazard assessment is required by NASA safety policy

- H₂ amounts > 10,000 lbs [OSHA Mandatory]
- Best practice per AIAA Guide [NASA Direction]
- Assessment methodology is specifically designed for H₂ hazards assessment
 - Identify hazards and evaluate risk
 - Methodology for thorough documentation
 - Based on *Guide for Hydrogen Hazards Analysis on Components and Systems* (WSTF-IR-1117-001-08)

Why Perform Hazards Assessment?

■ Systematically and objectively:

- Identify hazards
- Look at consequences
- Evaluate risk
- Identify mitigations
- Document and communicate
- Provide mechanism for control of hazards

■ Use to:

- Improve designs
- Evaluate safety
- Analyze failures

■ Formal Assessment:

- Obtain management “buy-in” and oversight
- Written documentation
- Reference for operations

Hazard assessment coupled with expert review is a primary component of best practice.

Applications for Hazard Assessment

May be applied at all stages in a system's existence:

- Initial concept
- Design review
- Operations
- Modifications to design or operation
- Decommissioning
- Post-mortem analysis following a failure

Underlying Approaches to Hazard Assessment

Historical approaches to hazard assessment

- None (trial & error by default)
- Prescriptive codes (from experience)
- Proactive Prescriptive (code based on best available information)
- Assess from basic principals, perhaps using models, predictive codes, and testing

Caution!

It is important to understand that most existing codes apply to specific applications (for example, storage), and that codes and standards for new applications either do not exist, or are under development.

Elements of Hazard Assessment

Step-wise methodologies have been developed to prevent failures in processes or facilities that deal with hazardous materials:

- Identify the facility/system
- Identify the hazards
- Conduct a hazard analysis
- Estimate the consequences of failures identified
- Estimate the frequency of occurrence of failures
- Estimate the risks
- Determine the acceptability of the risks
- Develop strategies for preventing the failures and diminishing adverse impacts

Types of Logic: Inductive vs. Deductive

■ Inductive Modeling

- Involves reasoning from individual cases to a general conclusion
- Induce the consequences of an event forwardly (bottom-up)
- The scenarios for an initiating event, which can have undesired consequences, are defined first
- Is useful in assuring that the analysis is broad enough to encompass all possible scenarios
- In general, provides answers to the generic question, “What happens if ..?”

■ Deductive Modeling

- Constitutes reasoning from the general to the specific
- Deduce the causes of an event backwardly (top-down)
- An event, for which causes are to be resolved, is defined first
- Has the benefit of focusing the analysis on the undesired event
- In general, answers the question, “What caused (or can cause) a failure or mishap to occur?”

Some Methodologies and Tools

Methodology or Tool (Source: Goldberg et. al.)	Advantages (A) and Limitations (L)
Cause-Consequence Analysis	<p>(A) Enables assessment of probabilities of coexisting faults or failures. End events need not be anticipated. Discrete levels of success or failure are distinguishable.</p> <p>(L) Addresses only one initiating challenge that must be foreseen by the analyst. May be very subjective as to consequence severity.</p>
Directed Graph (Digraph) Matrix Analysis	<p>(A) Allows the analyst to examine the fault propagation through several primary and support systems. Minimal cut sets, single-point failure, and double-point failures can be determined with less computer computation than with fault tree analysis (FTA).</p> <p>(L) Only identifies single point (singleton) and dual points (doubleton) of failure. Trained analyst, computer codes, and resources to perform this technique may be limited.</p>
Energy Flow/Barrier Analysis	<p>(A) Identifies hazards associated with energy sources and determines if barriers are adequate countermeasures.</p> <p>(L) Does not address coexisting system failure modes. Fails to identify certain classes of hazards, (e.g., asphyxia in oxygen-deficient confined spaces).</p>
Event Tree Analysis	<p>(A) Enables assessment of probabilities of coexisting faults or failures. Functions simultaneously in failure and success domain. End events need not be anticipated. Accident sequences through a system can be identified.</p> <p>(L) Addresses only one initiating challenge that must be foreseen by the analyst. Discrete levels of success and failure are not distinguishable.</p>

Some Methodologies and Tools (cont.)

Methodology or Tool	Advantages (A) and Limitations (L)
Failure Modes and Effects (and Criticality) Analysis	(A) Thorough methods of identifying single point failures and their consequences. A criticality analysis provides a risk assessment of these failure modes. (L) Can be extremely labor intensive. Does not address coexisting failure modes.
Fault Tree Analysis (FTA)	(A) Enables assessment of probabilities of coexisting faults or failures. May identify unnecessary design elements. (L) Addresses only one undesirable event or condition that must be foreseen by the analyst. Comprehensive trees may be very large and cumbersome.
Preliminary Hazard Analysis Probabilistic Risk Assessment	(A) Identifies and provides inventory of hazards and countermeasures. Provides methodology to assess overall system risks; avoids accepting unknown, intolerable, and senseless risks. (L) Does not address coexisting system failure modes. Performing the techniques of this methodology requires skilled analysts. Techniques can be misapplied and results misinterpreted.
Risk Assessment Matrix Success Tree Analysis	(A) Provides standard tool to subjectively assess risk. Assesses probability of favorable outcome of system operation. (L) Only used to assess risk of hazards, does not identify hazards. Addresses only one desirable event or condition that must be foreseen by the analysis. Comprehensive trees may be very large and cumbersome.

Challenges of Hydrogen Hazards Assessment

- Hydrogen releases differ from other fuels due to the extent of interaction with surroundings:
 - A leak at a point can grow into a cloud affecting a large area with many potential combustion hazards
 - Large flammability range and low MIE promote interaction of released hydrogen with ignition sources
 - Cryogenic issues are distinct from gaseous issues (releases can begin heavier-than-air and warm to become buoyant)
 - Hydrogen combustion processes are often intertwined with the geometry of the physical system and surroundings, such that flame acceleration and development of dangerous overpressures can occur
- Complexity of phenomena can obscure identification of hazards

Hydrogen Concerns Ranked

The primary hazards issues in descending order of priority:

1. Combustion
2. Pressure
3. Low Temperature
4. Hydrogen Embrittlement
5. Personnel Exposure

Hydrogen Combustion Properties of Note

In most hydrogen combustion scenarios the “Fire Triangle” concept is not adequate.

- Human senses challenged:
 - Flame is invisible in ambient light
 - Produces little IR that can be felt (emissivity < 0.1)
 - Produces **UV**
- Flammability varies with conditions
 - Broad range of flammable mixtures compared to most fuels
 - Factors include: mixture, pressure, temperature, initiation energy and combustion process
 - Micro-joule sources can ignite sensitive mixtures (at ambient conditions)

Hydrogen Combustion Properties of Note

- Gaseous combustion processes are dependent on surrounding geometry

- Flame acceleration can be substantial for geometries with $L/W > 8$ or flow obstructions (Nettleton 1987)
- Deflagrations readily approach sound speed in unburned gases and detonation speeds $> 400 \text{ m/s}$ to 1.5 km/s
- Detonation transition (DDT) in sensitive mixtures possible over run-up distances $\sim \frac{1}{2} \text{ meter}$
- Overpressures for sensitive H_2 -air mixtures:
 - Approach $8X$ in a closed vessel,
 - $15X$ for deflagration and detonation,
 - $\sim 45X$ for reflected detonation,
 - And larger pressures in dead-headed spaces (pressure piling) are possible, where $X \equiv \text{initial gas pressure}$.

- Condensed phase mixtures can be shock sensitive with TNT-like yields (*More than nitroglycerin!*)

Analysis Strategies for Hydrogen Combustion

Basic strategy: Seek specific concentration data for mixture formation and ascertain the flammability

- Below the flammability limit combustion does not occur
- Very lean or rich mixtures burn incompletely and flames propagate poorly
- With richer fuel concentrations, ignited mixtures exhibit complete burning,
- In more sensitive mixtures there is flame acceleration,
- And finally, in very sensitive mixtures transition to detonation is possible.

Analysis Strategies for Hydrogen Combustion

- Basic flammability *is not* the only criteria that determines the likelihood for a particular combustion process, and hence consequences
- Some mixing scenarios involve conditions that create concentration gradients such as leaks or jets into open air filled spaces
- Use a conservative approach when there is insufficient information
 - Assume the worst case,
 - Or a stoichiometric mixture, even though it may not be the most likely

Analysis Strategies - Initiation

- Many possible initiation sources (sparks, hot surfaces, metal fracture, etc..)
- The first goal of hazard assessment (best practice) is to locate potential sources of ignition, then assess their effect on the mixtures present.
- Assume for very sensitive mixtures that an ignition source will always be present.
- Ignition source strength influences flammability.
 - For example: Powerful electric discharges will initiate combustion in mixtures at lower pressures.
- For detonation, more powerful sources of shock are required to initiate mixtures with larger cell sizes.

Factors in the Analysis of Release

- Quantities of materials that can mix
- Conditions (temperature, pressure, mixture composition)
- Rate of release
- Extent (size) of cloud/plume
- Extent of mixing with oxidizer in systems where oxidizer is present
- Degree of confinement as determined by presence of piping, ducts, turbulence inducing obstacles, surfaces, walls, or density gradients
- Dimensions, volume
- Length to width (L/W) ratio to evaluate if conditions for flame acceleration are possible



Water vapor cloud formed from 1500 gallons of hydrogen released into a 30 ft diameter pond in 30 seconds with a 7-8 mph wind at the NASA White Sands Test Facility (1980)

Bounding Criteria for Combustion Assessment

Bounding Conditions	Flammability Limit	Comments
LFL Air in Tubes, ID 0.8–7.5 cm	~ 3.9–5 %	Upward propagation, Ambient conditions
ID 0.9–7.5 cm	~ 6–7 %	Horizontal propagation
ID 1.4–21 cm	~ 8–9 %	Downward propagation
UFL Static Ambient Air	75%	Upward propagation
UFL Static Oxygen	95.80%	Upward propagation
Low Pressure Flammability Limit in Air	20–30 %	6 kPa absolute pressure 45 mJ spark in 2-liter vessel
Low Pressure Limit in Oxygen	30–60 %	3 kPa absolute pressure, ~1 J spark
Laminar Burning Velocity H ₂ -Air no confinement at 298 K	17%	1 m/s
	42%	3.5 m/s (Benz et al. 1988)
	64%	2.2 m/s (Benz et al. 1988)

Bounding Criteria for Combustion Assessment

Bounding Conditions	Flammability Limit	Comments
Laminar Burning Velocity, H ₂ -Air, no confinement at 298 K (cont.)		9 m/s at stoichiometry
Flame Speed in Pipes, IDs 5–30 cm	< 10 %	No acceleration
	10 % to < 13 %	100 m/s to < 200 m/s, steady and insensitive to obstacles
H ₂ - Air, 10 < L/D < 40	> 13 %	Velocity limited to sound speed of products (600 to 1000 m/s) – choked flow
	> 17 %	DDT and CJ velocities (1700 m/s)
Cell Size, Stoichiometric H ₂ -Air	1.6 cm	Cell size increases for non stoichiometric mixtures
Cell Size, Stoichiometric H ₂ -O ₂	0.16 cm	Cell size increases for non stoichiometric mixtures
Solid air in Liquid Hydrogen	> 40 %	Highly shock sensitive. Detonable with effects similar to high explosives
Solid oxygen in Liquid Hydrogen	If % O ₂ > % H ₂	Shock sensitive for stimuli of 100 to 250 MPa (less than nitro-glycerine)

Condensed Phase Issues

- LH₂ spills dissipate by absorption of heat from the air and by heat transfer through gas near solid surfaces
- 40 % (LDL) solid air in LH₂ is more shock sensitive than nitroglycerin (UDL is not known)
- LH₂-LOX Mixing: Yield is proportional to surface area of mixing (WSTF drop tower/pan tests 1995)

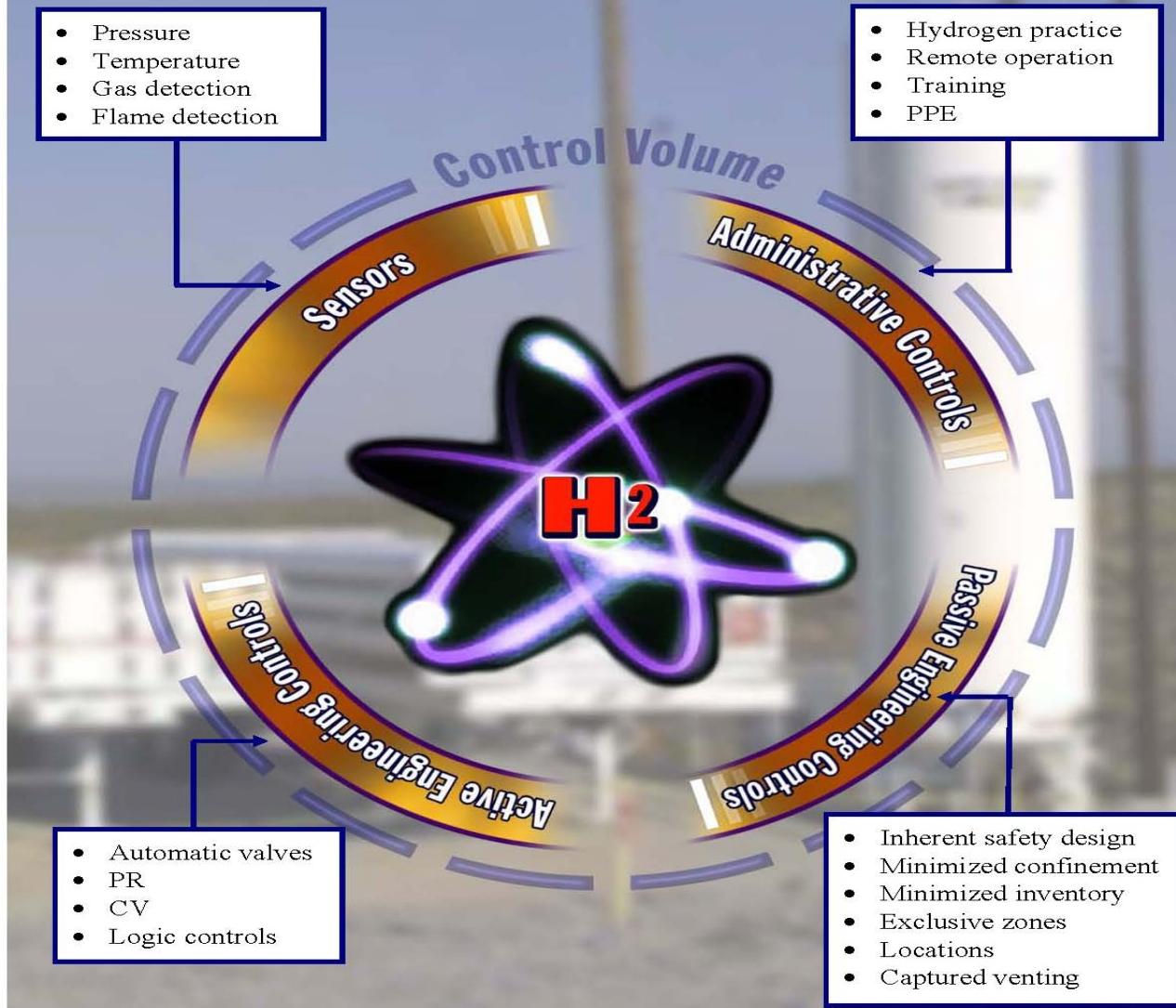


Explosion of 50 lb LOX/LH₂ at High Energy Blast Facility (WSTF 1995)

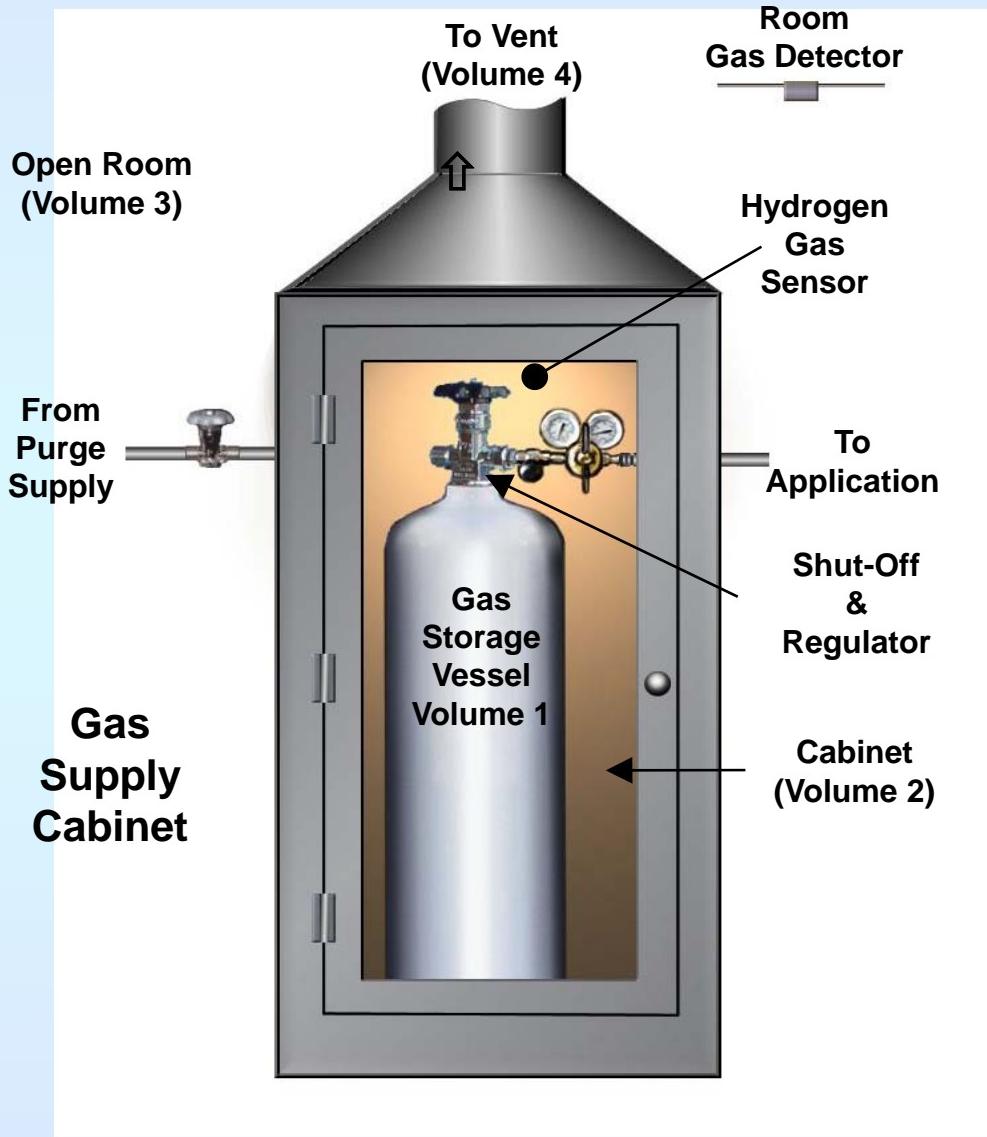
Hydrogen Hazard Assessment Protocol (HHAP) – Basic Concept

- Typically a H₂ event is defined by:
 - Unintended release of H₂ derived energy (pressure or temperature differential)
 - Incursion of reactive material (causing mixing)
 - Release of H₂(causing mixing) into a volume or space.
- System layout, design, controls and operations are elements that define where the volumes of interest are:
 - Hydrogen-wetted portions of a system
 - Interstitial spaces between components
 - Environment surrounding the system

Elements of Hydrogen Control



Volumes in a Simple Scenario



Volume	Controls
1	Vessel walls, shut-off valve, regulator
2	Cabinet wall, purge, vent, gas sensor that controls purge and alarm
3	Gas detector in room, ventilation to code
4	Location to code, GH ₂ freely dissipates

HHAP

The HHAP provides a framework and suggestions for developing:

- An analysis strategy
- Criteria for defining volumes
- A methodology for analysis
- A means for documentation

Overview of Methodology

Methodology uses both inductive & deductive approaches. Process elements include:

- Identification of volumes for analysis
- Assessment of factors/potential causes that might contribute to an unintended release
- Evaluation of characteristics of the release within the volume
- Determination of potential hydrogen behaviors arising from the release
- Evaluation of consequences and associated risks
- Recommendations for mitigation

Hazards Assessment Prerequisites

- Understand analysis scope
- Have detailed design information
 - Up-to-date schematics
 - Vendor data
 - Obtain specifications for all materials exposed to H₂
- Have information necessary to evaluate all leak paths
- Assemble critical expertise:
 - Subject matter experts
 - Skilled meeting facilitators
 - Designers
 - System “owners”
 - Facility managers

Initial Considerations

Before convening team:

- System owners set agenda/scope of assessment
- Facilitators ensure team is ready (homework done)
- Sequester team from distractions
- Provide comfortable environment
 - Use breaks
 - Provide refreshments

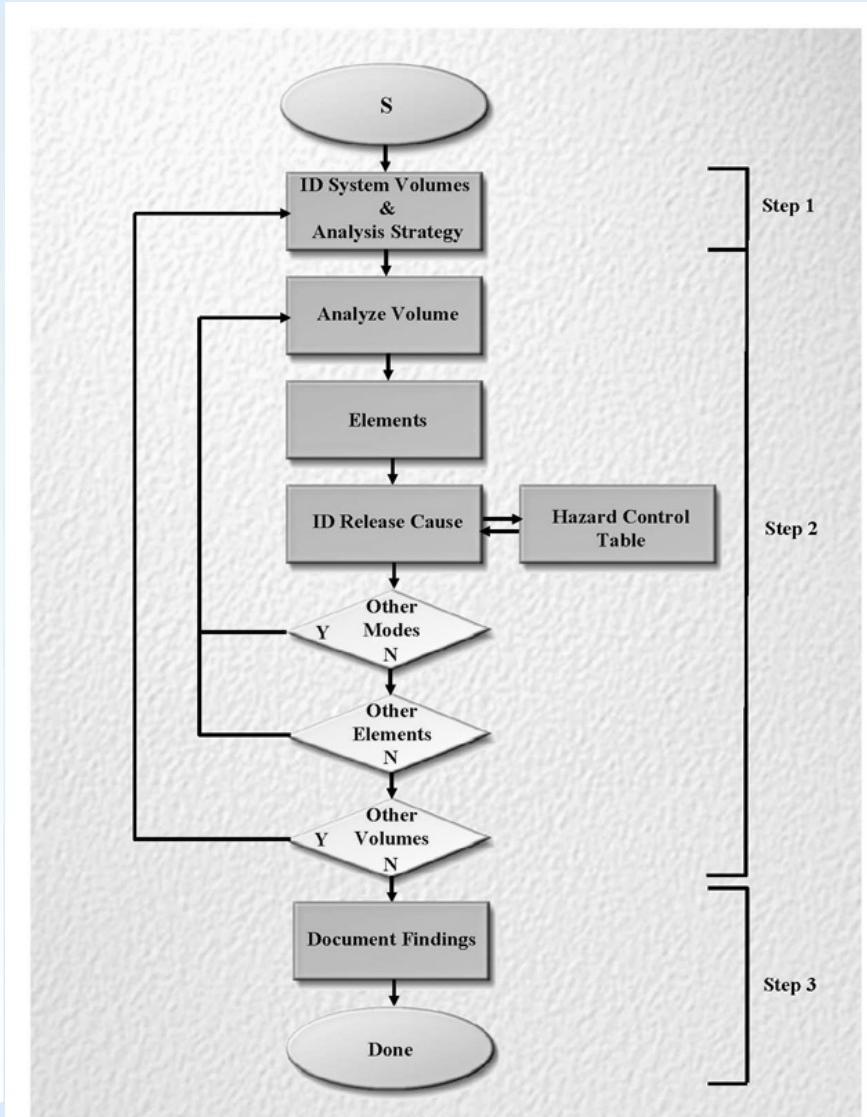
Questions to Consider

- What failure modes involve H₂?
- Where can combustible mixtures form?
- What ignition sources exist?
- What combustion mechanisms are active?
- What are the combustion effects?
- What are the consequences?
- What are the overall risks to system, users, mission, or business?

Process Flow Diagram

STEP 1 – Analysis Strategy

- Determine which portions of a system require hydrogen analysis
- Discern the distinct volumes in which hydrogen is either controlled (wetted)
- Or into which hydrogen or hydrogen related energies may be unintentionally released.
- Prioritize which volumes and elements should be considered first.
- Identify attributes in common between volumes or elements to minimize effort (components, materials, functions, etc..)



Process Flow Diagram

Step 2, for components:

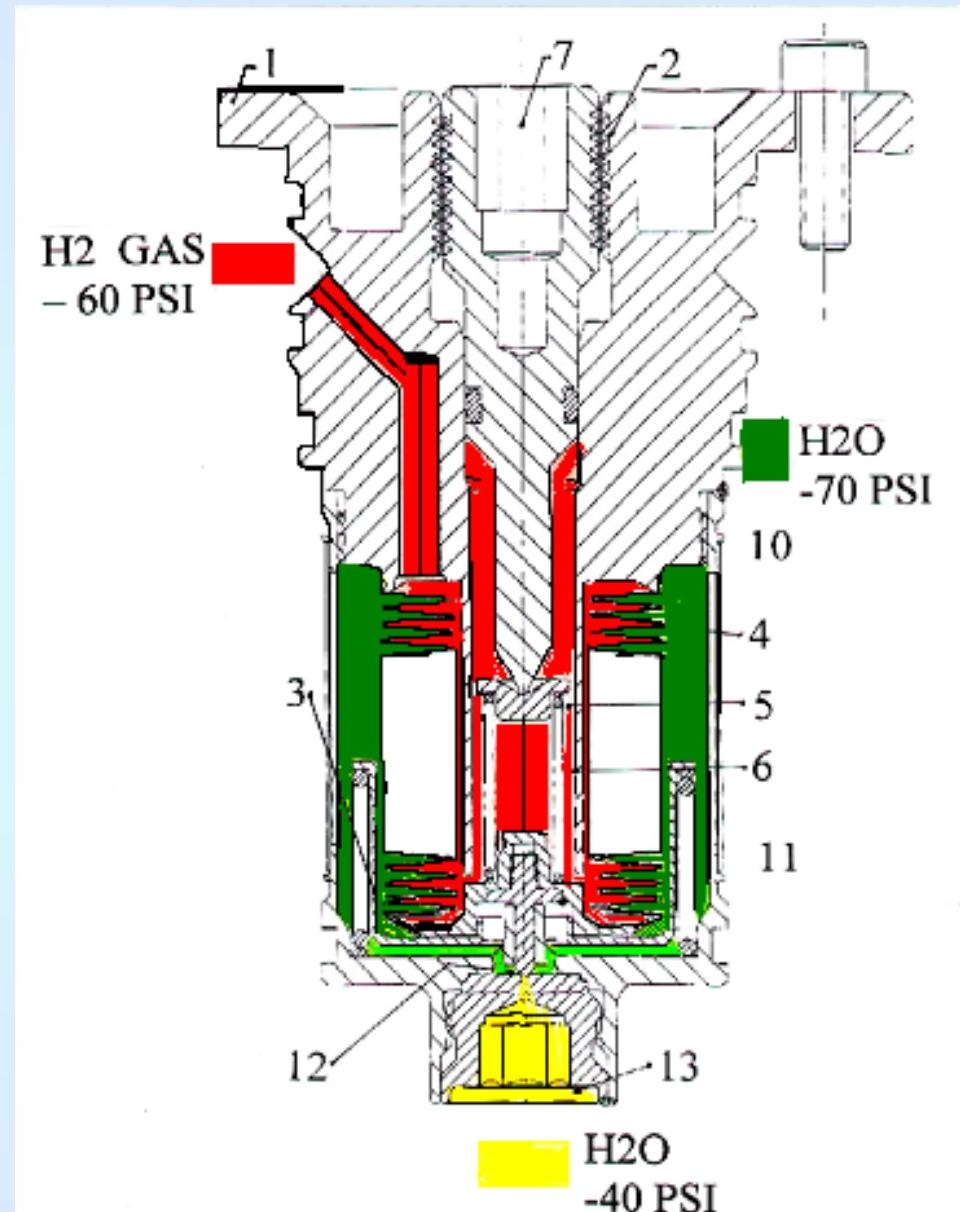
- Identify the functional modes that involve hydrogen.
- Perform analysis of materials wetted by hydrogen.
- Look for circumstances and failure modes that can contribute to a hydrogen release.

Step 2, for operations with personnel look for:

- Deviations from best practice that may lead to a hydrogen release
- Unnecessary exposure
- Interaction between elements, and kindling chain issues
- Other potential issues as required
- The potential for operator error

Component schematic illustrating type of data required for analysis:

- Materials Identified
- Analysis shows types of hydrogen exposure



Materials Assessment Table with sample entries

COMPONENT ID	Regulator	MANUFACTURER	Carleton	MEDIA	GH ₂ /water			
PRESSURE RATING	160 psig	MODEL NO.	B42487-1					
NOTES								
MATERIALS OF CONSTRUCTION								
Metal / Softgood / Lubricant		Function within Component						
304L		Bellows Mount Plate, Poppet/End Plate, Bellows, Spring Seat						
17-7 PH CH900		Adjusting spring, Load spring						
17-4 PH H1075		Seat retainer						
300 series SS		Housing						
PEEK		Seat						
Viton		Manifold seal						
EPR		O-Ring adjusting seal						
COMPONENT USE ENVIRONMENT								
Use Scenario	Back pressure regulator	Operating Conditions			Worst-Case Condition			
		Pressure	Temperature	Other	Pressure	Temperature	Other	
Flight	65 psia MDP	70 to +85 °F	29.1 g	80 psia MOP	70 to +100 °F	Per Spec.		

Materials Assessment Table

with sample entries (cont'd)

POTENTIAL FAILURE CAUSES			PROBABILITY OF FAILURE				
Is this cause present?		Yes Or No	Leaks Externally	Leaks Internally Fails Open	Fails Closed	Generates Contaminants	Other
Properties of Component Materials	Diffusion/ Permeation	Y	1				
	Chemical Reaction	N					
	Temperature Compatibility	N					
	Expansion/ Contraction	N					
	H-Embrittlement	Y	1	2	N/A	1	
	Other	N					
System Conditions	Mechanical Stress / Vibration	Y	0	0	0	1	
	Flow Regime	N					
	Deformation	N					
	Resonance	N					
	Liquid Lockup	N					
	Water Hammer / Surge Pressure	N					
	System Catalyst Contamination	Y					3
	Liquid Air Formation	N					
	Other	N					

Probability Rating: **0** = Almost Impossible **1** = Remotely Possible **2** = Possible **3** = Probable **4** = Highly Probable

Mixing and Combustion

- Identify the cause of the hydrogen release
- Evaluate potential hydrogen mixture(s) that may arise within the volume
- Assess potential effects for non-ignition and combustion events:
 - Evaluate which non-ignition events are possible
 - Fire, deflagration, detonation may all be possible
 - Evaluate potential combustion processes and effects in the context of the mixing event and scenario confinement
 - Evaluate flammability
 - Ignition mechanisms based on the elements and other ignition sources present in the volume

Assessment Tasks

- Note controls or controlling factors that mitigate a hazard as well as circumstances that might interfere with the controls. Summarize the effect on potential reactions
- Assess the likelihood from ignition criteria
- Evaluate the severity of the reaction effect from established criteria
- Consider potential mitigations for unacceptable hazards and deleterious effects and note proposed controls
- Assess mitigated reaction effects

Assessment of Risk of Ignition

Ignition Rating	Code	Criteria	
		Characteristic Elements	Mixture Flammability
Not Possible	0	Not at all present	Nonflammable
Remotely Possible	1	All present	Nonflammable
		Not at all present	Flammable
Possible	2	All present and active	Flammable
Probable	3	All present and some are strongly active	Flammable
Highly Probable	4	All present and all are strongly active	Flammable

Assessment Criteria for Event Severity

Rating	Code	Personnel Safety	System Objectives	Functional Capability	Example
Negligible	A	No injury to personnel	No unacceptable effect on production, storage, transportation, distribution, or use as applicable	No unacceptable damage to the system	There is no personnel access, kindling chain, or ignition probability greater than 0
Marginal	B	Personnel-injuring factors can be controlled by automatic devices, warning devices, or special operating procedures	Mission/Objective can be accomplished by using available redundant operational options, or resumed after acceptable repair	No more than one component or subsystem damaged. This condition is either repairable or replaceable within an acceptable time frame on site	There is a kindling chain, and ignition probabilities are greater than 0. In addition, access to the area is controlled in a formally documented procedure and barricades are used
Critical	C	Personnel may be injured (1) operating the system, (2) maintaining the system, or (3) by being in the vicinity of the system	Production, storage, transportation, distribution, or use as applicable impaired seriously	Two or more major subsystems are damaged. This condition requires extensive maintenance	There is a kindling chain, and ignition probabilities are greater than 0. In addition, access is limited by a shield or distance, but there are no formal access procedures or barricades used
Catastrophic	D	Personnel suffer death or multiple injuries	Production, storage, transportation, distribution, or use as applicable rendered impossible—major unit is lost	No portion of the system can be salvaged—total loss	There is a kindling chain, ignition probabilities are greater than 0, and direct exposure is required for operation

Sample Hazard Control Table

Item	Release Cause	Seal fails on flange for pipe containing 30 psi, 100 K cold hydrogen gas					
1	Release Description	Cryogenic gas release into open space. No further confinement in exclusion zone					
Hazard Consideration		Existing Controls	Reaction Effect	Code	Recommended Action/Control	Final Code	STATUS
Non-Ignition Probabilities	Cold Exposure	Use appropriate PPE	None. Frostbite hazard mitigated	1 A	None	1 A	
	Gas/Liquid Release	Hydrogen gas detector above flange	Detector will trigger	3 A	None	3 A	
	Pressurized Release/Jet	None			None		
Probabilities for Combustion Processes	Heat	None			None		
	Flame	None	Ignition is possible and may be triggered by approaching personnel. Hazard would include burns	2 B	Upon alarm, appropriate safing procedures must be followed. Regardless of system status, personnel should approach with caution. Operational control prevents hazard to personnel	2 A	Accept, as noted
	Cloud Fire	None	Will dissipate	0	None		
	Jet Fire	None	Insufficient pressure	0	None		
	Deflagration	None	Insufficient mixture	0	None		
	Gas Detonation	None	No ignition source	0	None		
	Condensed Detonation	None	No mixture	0	None		
	Other		Not identified				

Code: 0 Not possible

1 Remotely Possible

2 Possible

3 Probable

4 Highly Probable

A Negligible

B Marginal

C Critical

D Catastrophic

Summary – What is Achieved?

- ✓ Hydrogen scenarios are systematically identified using a combination of deductive and inductive approaches
- ✓ Assessment specifically tailored for hydrogen behavior:
 - ❖ Organized around volumes into which hydrogen release can occur
 - ❖ Analysis of mixing specifics, of flammability, available ignition sources, surrounding confinement, and combustion process together define the hazard
 - ❖ Mitigations built into the system are recognized
- ✓ Non-combustion and combustion hazards are identified

Summary – What is Achieved?

- ✓ Severity and qualitative risk are assessed
- ✓ New mitigations are captured
- ✓ This information is systematically organized and documented

The end product is a compilation of hazards, mitigations, & associated factors to facilitate decision making and achieve best practice!

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